

# 6-7 MeV CHARACTERISTIC $\gamma$ -RAY SOURCE USING a PLASMA OPENING SWITCH and a MARX BANK\*

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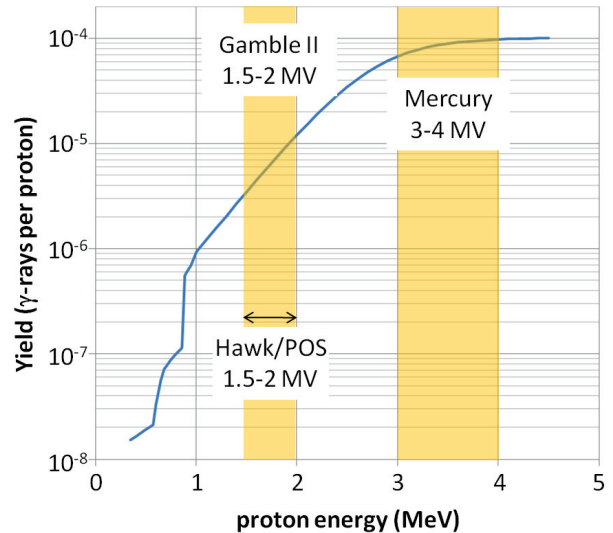
## Abstract

A 640 kV Marx bank and plasma opening switch (POS) produce an intense pulse of MeV protons that stop in a fluorine-bearing target. The  $^{19}\text{F}(\text{p},\alpha\gamma)^{16}\text{O}$  reaction produces 6- to 7-MeV characteristic  $\gamma$ -rays that can induce fission reactions in fissionable materials, such as depleted uranium (DU). Some fission reactions are also induced by neutrons generated by proton and/or deuteron reactions in the target, indicating that this system could be used to produce a mixed source of  $\gamma$ -rays and neutrons. Experimental results are presented, and future options are described to improve this kind of mixed source.

## I. INTRODUCTION

Characteristic  $\gamma$ -rays can be produced from the interaction of protons with various nuclei. One example is the  $^{19}\text{F}(\text{p},\alpha\gamma)^{16}\text{O}$  reaction which produces 6.13, 6.92 and 7.12 MeV  $\gamma$ -rays with a well-known absolute yield [1,2]. In principle, these  $\gamma$ -rays can be used for nuclear material detection.[3] Figure 1 is a plot of the thick target yield for this reaction vs. proton energy, and indicates voltage ranges used to produce these  $\gamma$ -rays on three different generators at the Naval Research Laboratory. A 300 kA, 50 ns pulse of 2 MeV protons from the Gamble II generator, incident on a PTFE [Teflon ( $\text{C}_2\text{F}_4$ )<sub>n</sub>] target produces about  $3 \times 10^{11}$  characteristic  $\gamma$ -rays.[4] The 4 MeV, 90 kA proton beam from the Mercury generator produces  $1.4 \times 10^{12}$   $\gamma$ -rays.[5] The Mercury  $\gamma$ -rays induced photofission reactions in a DU target and neutrons from the fission reactions were detected.[6] The Hawk/POS experiments are the subject of this paper.

For some applications, it may be desirable to use a lower voltage, more compact, less expensive pulsed power generator to produce an intense pulse of characteristic  $\gamma$ -rays for nuclear materials detection. Hawk is much smaller than either Gamble II or Mercury. The plasma opening switch (POS) replaces the pulse-forming sections of the more traditional generators making it more compact. This technique was first demonstrated in the 1980's.[7-9] The experiment



**Figure 1.** Thick target yield for the  $^{19}\text{F}(\text{p},\alpha\gamma)^{16}\text{O}$  reaction on a PTFE target, and voltage ranges for Hawk, Gamble II and Mercury experiments.

described here is the first attempt to produce  $\gamma$ -rays using the Hawk generator with a POS.

## II. EXPERIMENTAL SETUP

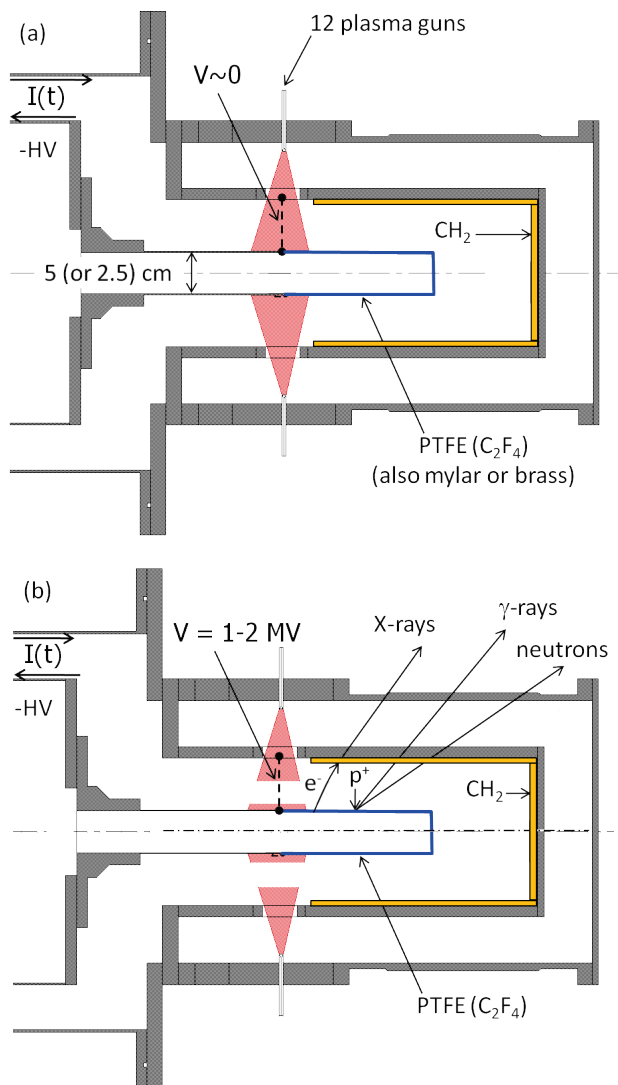
Hawk is a 200 kJ Marx bank immersed in oil. The erected capacitance and voltage are 1  $\mu\text{F}$  and 640 kV, respectively. With a short circuit load, the sinusoidal current rises to 700 kA in 1.2  $\mu\text{s}$  due to the self-inductance (600 nH) of the circuit. The load voltage is increased using the POS in vacuum. The vacuum section of Hawk, including the POS, is shown in Fig. 2a. The POS consists of 12 plasma guns made from coaxial cables that inject ionized plasma radially inward between two coaxial conductors prior to firing the generator. The POS plasma conducts the generator current as a short circuit for about 700 ns, then the impedance increases resulting in voltages exceeding 1 to 2 MV. Figure 2b shows the POS in the “open” or high-voltage phase, with a vacuum gap in the plasma. High-energy electron- and ion-beams form in the plasma-filled coaxial region, with ions from the plasma and the polyethylene ( $\text{CH}_2$ ) lined outer conductor surface bombarding the center conductor. The

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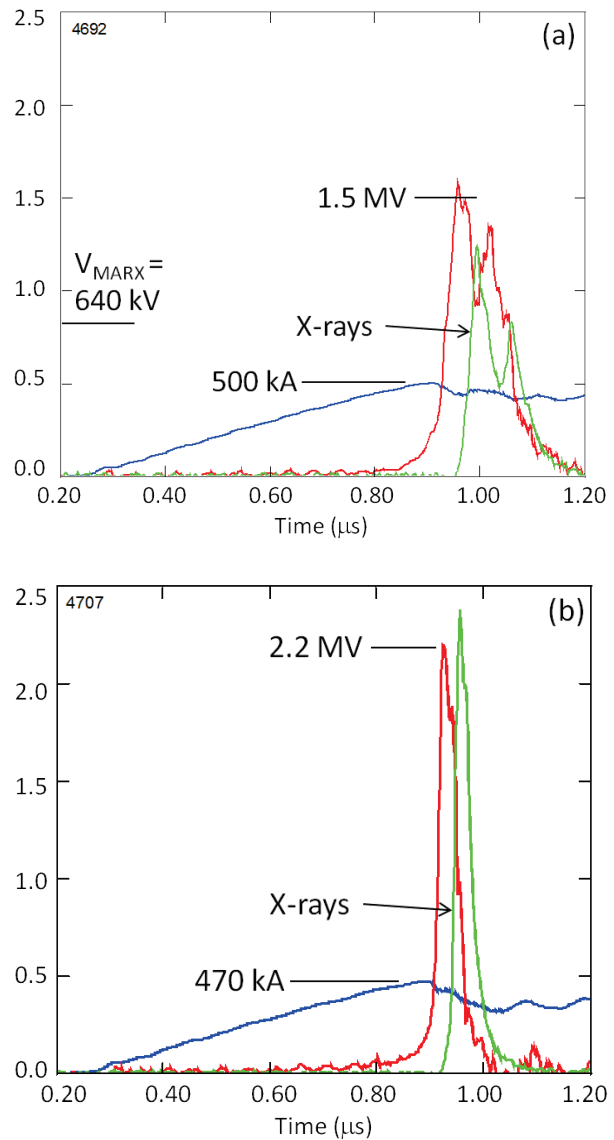
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**Figure 2.** Hawk setup with POS for producing characteristic  $\gamma$ -rays. (a) The initial, closed POS short-circuits the generator. (b) The POS in the open state produces electron and ion beams that produce x-rays, characteristic  $\gamma$ -rays and neutrons.

center conductor is covered with a thin PTFE sheet from the center of the POS plasma injection region to the downstream end, to provide a characteristic  $\gamma$ -ray target. Electrons stop in the CH<sub>2</sub>-lined outer conductor and produce bremsstrahlung (x-rays). Neutrons can also be produced by various (p,n) and (d,n) reactions in the PTFE target.

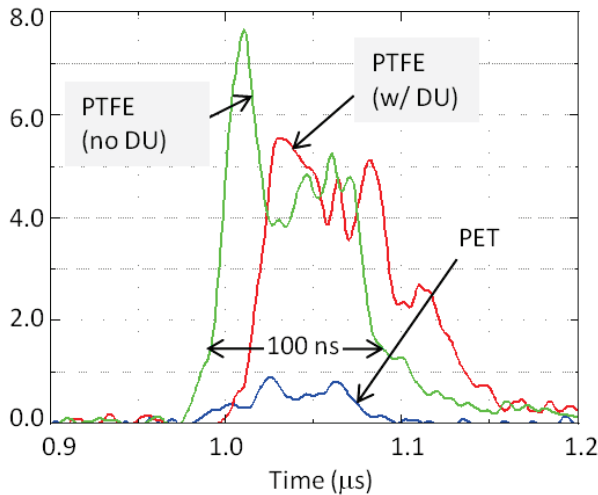
The source of the ions is either (or both) the injected plasma or the anode plasma created on the electron-heated surface of the CH<sub>2</sub>. The plasma gun PTFE insulation is not the primary proton source. Impurities from residual water vapor and/or hydrocarbons are the only source of protons in the injected plasma. The plasma formed at the CH<sub>2</sub> surface is a source of protons, but the outer conductor is far from the center conductor, reducing the ion current density from that source.



**Figure 3.** Current (blue), voltage (red) and x-ray (green) data from shots with (a) 5-cm center conductor diameter and (b) 2.5-cm center conductor diameter.

### III. RESULTS

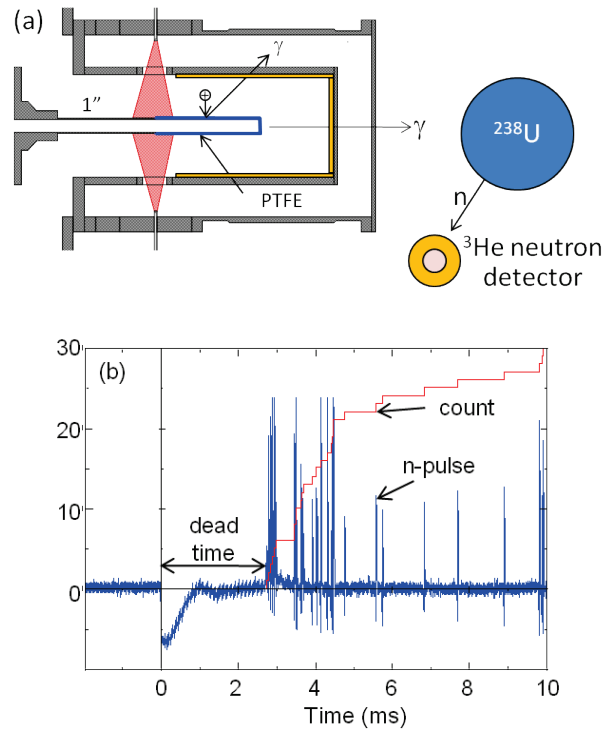
The electrical behavior of the Marx/POS system is illustrated by data in Fig. 3 for a 5-cm diameter center conductor (Fig. 3a) and a 2.5-cm diameter center conductor (Fig. 3b). The current is measured in vacuum between the Hawk oil-vacuum insulator and the POS. For both the 5- and 2.5-cm center conductors, the current increases to about 500 kA in 600 ns while the POS is a short circuit. Then the POS opens and the current decreases. The voltage is measured on the oil side of the insulator and is inductively corrected to the center of the POS as indicated in Fig. 2. The POS voltage is essentially zero during the short circuit phase. The voltage increases rapidly to 1.5 MV for the 5 cm center conductor (Fig. 3a)



**Figure 4.**  $\gamma$ -ray detector (photomultiplier) signals for three shots with a 5-cm center conductor and similar electrical parameters, indicating  $\gamma$ -ray production when a fluorinated ion target (teflon) is used instead of a non-fluorinated ion target (mylar).

and 2.2 MV for the 2.5 cm center conductor (Fig. 3b). These peak voltages are 2.3 and 3.4 times greater than the erected Marx voltage (640 kV) for the 5 and 2.5 cm center conductors, respectively. The higher voltage with smaller radius is attributed to larger magnetic field in a similar-size vacuum gap formed in the plasma.[10] The x-ray signals in Fig. 3 have the same shapes as the voltage waveforms, but are not synchronized with the voltage waveforms. The correlation of voltage and x-ray signal shapes indicates that energetic electrons are striking the outer conductor. The higher voltage in the 2.5-cm case often results in premature insulator flashover, making the voltage pulse duration shorter than it otherwise would be. The energy coupled to the load is calculated by integrating the current-voltage product. The coupled energy is as large as 120 kJ for shots with the 5-cm center conductor, which is about 60% of the 205 kJ stored in the Marx. The coupled energy for these Hawk shots is more than double the typical energy coupled to ion-beam diodes on Gamble II and Mercury. The coupled energy is similar for the 2.5-cm shots when the insulator does not flash, but is significantly less if the insulator flashes during the high-voltage phase.

During the high-voltage phase, protons should have sufficient energy to produce characteristic  $\gamma$ -rays (see Fig. 1). The  $\gamma$ -rays are monitored using a scintillator-photomultiplier inside a 4-cm thick lead enclosure located 2.3 m from the axis of the center conductor. The detector is also shielded by 0.9 m of concrete to attenuate the bremsstrahlung contribution to the signal. This shielding arrangement works well for the 5-cm center conductor as shown in Fig. 4. Two shots with PTFE on the center conductor surface (as shown in Fig. 2) produced much larger signals than a shot with PET [Mylar ( $C_{10}H_8O_4$ )<sub>n</sub>] on



**Figure 5.** (a) Setup for detecting fission neutrons; (b) signal (n-pulse) and pulse count from the  $^3\text{He}$  detector using the 2.5-cm POS center conductor.

the center conductor. This diagnostic is clearly measuring characteristic  $\gamma$ -rays. This diagnostic is not as effective with the 2.5 cm center conductor, because at higher voltage the more intense and higher-energy bremsstrahlung overwhelms the smaller  $\gamma$ -ray signal.

The arrangement for detecting fission neutrons from DU is shown in Fig. 5a with the 2.5 cm center conductor covered with PTFE. For some shots, the PTFE was replaced with PET or brass. The DU is a 20-cm diameter, solid sphere positioned on axis, close to the vacuum chamber. A  $^3\text{He}$  neutron detector [6] about 45 cm tall (perpendicular to the plane of Fig. 5a) is indicated by the concentric circles. The inner circle represents a high pressure  $^3\text{He}$  tube and the outer circle represents a moderator of polyethylene, cadmium, and Flexi-boron that helps match the detector's response to the shape of the fission neutron spectrum. A preamp and integrator convert the signal resulting from a single neutron interaction in the gas into a  $\sim 10$ - $\mu\text{s}$  wide pulse suitable for digital recording for many seconds after a shot.

Neutron-detector data from the shot with the greatest number of fission-neutron pulses are shown in Fig. 5b. This shot used the setup in Fig. 5a, with electrical data shown in Fig. 3b. The coupled energy was only 45 kJ due to early insulator flashover. The detector electronics recover from the radiation and EMP from the generator pulse after 2.7 ms. Thirty neutron pulses are recorded between 2.7 and 10 ms. More than 300 pulses are recorded in the first 2 seconds. When the DU object is removed, no pulses are measured in 2 seconds. Similar

shots with a lead object instead of DU result in zero pulses in 2 seconds. ( $^{207}\text{Pb}$  produces photoneutrons when exposed to 7.1-MeV  $\gamma$ -rays, but they probably arrive at the detector before the detector recovers.) These measurements suggest that the neutrons detected when the DU is present are delayed neutrons (neutrons from decaying daughter products) that result from fission reactions. It is not clear how many of the fission reactions are caused, as intended, by characteristic  $\gamma$ -rays and how many are caused by ancillary neutrons from other beam-target reactions in the source.

The number of neutrons detected in the first 0.2 seconds for experiments with the 5 cm center conductor is summarized in Fig. 6. For these shots, the  $\gamma$ -ray detector signal is integrated to give a relative measure of the  $\gamma$ -ray yield. Shots with different objects (DU, Pb, or none) are indicated by symbols. The number of detected neutron pulses from DU increases with the  $\gamma$ -ray yield. No neutron pulses are detected in this time interval when DU is removed or replaced by lead.

Replacing the PTFE target with PET eliminates the  $^{19}\text{F}(p,\alpha\gamma)$  characteristic  $\gamma$ -rays, but some neutron pulses were still detected with DU when the center conductor diameter was 2.5 cm (about ten times fewer than with PTFE). These fissions were probably caused by neutrons from the  $^{12}\text{C}(d,n)^{13}\text{N}$  and  $^{13}\text{C}(p,n)^{13}\text{N}$  reactions. The (d,n) reaction has a low threshold (0.33 MeV), but the natural abundance of deuterium is small (0.015%). The (p,n) reaction has a high threshold (3.23 MeV), greater than the POS voltage (2.2 MV), and the natural abundance of  $^{13}\text{C}$  is small (1.1%).  $^{13}\text{N}$  decays with a 10 minute half-life. Ions with energies exceeding the POS voltage are a ubiquitous feature of these systems [11], so this (p,n) reaction cannot be completely eliminated based solely on the high threshold energy.

More definitive evidence for ion energies exceeding the POS voltage was obtained by covering the entire length of the 2.5 cm center conductor with a thin brass sheet. More (3.5 times) fission neutrons were detected in

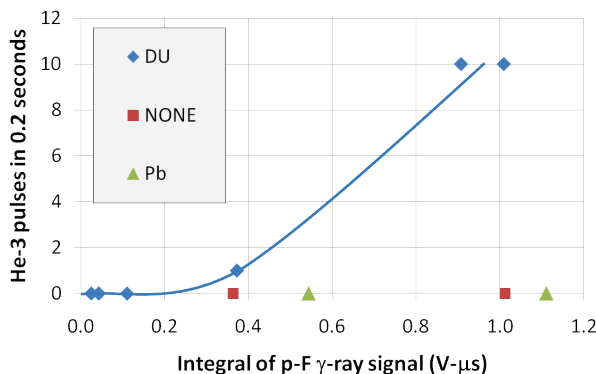
this case than for a comparable shot with PTFE covering the center conductor. The brass was radioactive after the shot and was monitored using a Geiger counter for about 1 hour. The radiation decayed with a  $\sim 38$  min half-life. The lowest threshold reaction that could produce this activity is  $^{63}\text{Cu}(p,n)^{63}\text{Zn}$ , with a 4.22 MeV threshold and 38.5 min half-life. Protons with energies greater than double the POS voltage have been detected in similar experiments in the past.[11] There is probably a collective-acceleration mechanism that produces a small population of multi-MeV ions.

The brass sheet was removed, unrolled and placed flat on an image plate for 30 minutes starting 1 hour after the shot. The purpose was to determine where ions strike the center conductor. The setup is shown in Fig. 7a and the resulting image is in Fig. 7b. The image plate response is proportional to dose from beta emission. Apparently, ions strike the entire length of the center conductor, both upstream and downstream of the injected plasma, with obvious non-uniformities and concentrated regions near the downstream end of the center conductor.

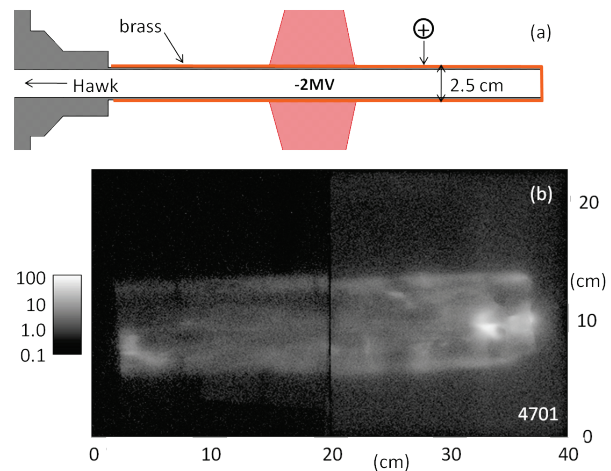
The reaction responsible for the majority of the source neutrons that induced fission in the DU is probably the  $^{65}\text{Cu}(p,n)^{65}\text{Zn}$  reaction, which has a lower threshold (2.2 MeV) and a larger yield than the  $^{63}\text{Cu}(p,n)^{63}\text{Zn}$  reaction.[12] The natural abundance of  $^{65}\text{Cu}$  is 31% and  $^{65}\text{Zn}$  has a 244 day half-life. This decay would have been difficult to measure with the Geiger counter. Neutrons from this reaction would have sufficient energy to induce fission in DU.

Using a 5-cm center conductor covered with brass, the number of detected neutrons was about 3 times less than the number detected using PTFE. Evidently, the proton energy scales with the POS voltage so that fewer neutrons have sufficient energy to produce fission reactions in this case.

In addition to the  $^{12}\text{C}(d,n)^{13}\text{N}$  and  $^{13}\text{C}(p,n)^{13}\text{N}$  reactions, two reactions on fluorine in the PTFE target



**Figure 6.** Neutron pulses recorded by the  $^3\text{He}$  detector in 0.2 seconds as a function of the  $\gamma$ -ray yield using the 5-cm diameter POS center conductor. Symbols indicate object materials.



**Figure 7.** (a) Setup with brass covering the 2.5 cm center conductor. (b) Image plate record of radiation from the flattened brass sheet.



could produce neutrons. The  $^{19}\text{F}(\text{p},\text{n})^{19}\text{Ne}$  reaction has a 4.2 MeV threshold and  $^{19}\text{Ne}$  has a 17.2 second half life. In contrast, the  $^{19}\text{F}(\text{d},\text{n})^{20}\text{Ne}$  reaction has a positive Q-value, no radioactive products, and in this case produces neutrons with maximum energies greater than 10 MeV. While it is clear that both  $\gamma$ -rays and neutrons can produce fission reactions in DU in this experiment, it is difficult to determine their relative strengths. This is an area for further investigation.

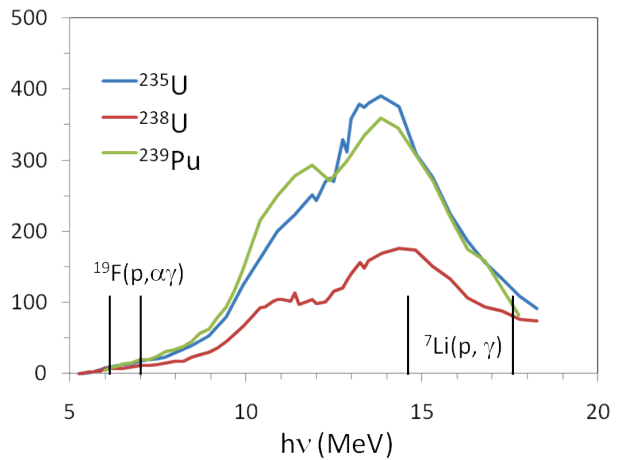
#### IV. SUMMARY and FUTURE WORK

A 640 kV Marx bank and POS produces a multi-MeV proton beam that generates 6- to 7-MeV  $\gamma$ -rays from the  $^{19}\text{F}(\text{p},\alpha\gamma)^{16}\text{O}$  reaction. These characteristic  $\gamma$ -rays induce photofission reactions in a DU sphere. Delayed fission neutrons are detected using a nearby  $^3\text{He}$  detector. Neutrons from (p,n) and (d,n) reactions with various target nuclei (C, F, Cu) also induce fission reactions in DU. Some of the neutron-generating reactions require protons with energies greater than twice the POS voltage.

These experiments demonstrate the feasibility of using a simple pulsed power generator (640 kV Marx bank) with a POS (to increase the voltage and decrease the pulse duration) to generate  $\gamma$ -rays suitable for nuclear detection applications. The current and voltage at the time of maximum power are similar to those for the much larger Gamble II generator using an ion-beam diode, and the coupled energy is greater. It is not known if the proton currents are comparable because the  $\gamma$ -ray measurements were not calibrated and the Hawk experiments did not have an independent ion current diagnostic. Furthermore, the ion source in the Hawk experiments could be the POS plasma or the inner surface of the outer conductor. Distinguishing these ion beam sources is a subject for further study and experiments.

Improving this type of pulsed power system for active detection applications could include several changes. The proton fraction in the ion beam may be increased with a hydrogen-gas plasma source, using one of the methods demonstrated previously.[13, 14] The gas could be a mixture of  $\text{H}_2$  and  $\text{D}_2$  to increase the neutron output. If the majority of the protons are from the POS plasma, the plasma can be an easily-replenished anode of an ion diode for repetitive operation. (Solid anodes in high-power ion diodes are often destroyed during a single shot and would be awkward to replace in a repetitive system.)

Another option is to use a different target material, such as lithium, instead of fluorine. Figure 8 shows photofission cross sections for  $^{235}\text{U}$ ,  $^{238}\text{U}$  and  $^{239}\text{Pu}$  vs. photon energy.  $\gamma$ -ray energies from  $^{19}\text{F}$  and  $^7\text{Li}$  are indicated by vertical lines. The  $^{19}\text{F}$   $\gamma$ -rays have energies slightly higher than the photofission threshold in these materials, and the photofission cross sections are strongly energy dependent. One of the  $^7\text{Li}$   $\gamma$ -rays has energy (14.7 MeV, 37% branching) near the peak of the cross sections and one  $\gamma$ -ray has higher energy (17.6 MeV, 63%



**Figure 8.** Photofission cross sections (in mbarn) as functions of photon energy.

branching) where the cross section is still much greater than for the  $^{19}\text{F}$   $\gamma$ -rays. These  $\gamma$ -rays may be preferable for detection applications when the number of fissions per  $\gamma$ -ray, or fissions per dose-to-humans is important. For  $^{235}\text{U}$ , the fissions per dose-to-humans for  $^7\text{Li}$   $\gamma$ -rays is about 7 times greater than for  $^{19}\text{F}$   $\gamma$ -rays. Another advantage of the  $^7\text{Li}$  reaction is lower proton energy; this reaction has a single resonance at 441 keV. A lower-voltage generator could therefore be used, further simplifying the system.

The use of  $^7\text{Li}$   $\gamma$ -rays instead of  $^{19}\text{F}$   $\gamma$ -rays also has several disadvantages, including increased activation and increased photoneutron yield from many common environmental materials that could make detection of fissionable materials more difficult. The main disadvantage of the  $^7\text{Li}$  reaction, however, is lower yield (about  $10^{-8}$   $\gamma$ -rays/proton, or 1000 times less than the yield from 2-MeV protons on  $^{19}\text{F}$ ). This inefficiency can be overcome if the generator produces a pulse with a sufficient number of 441-keV protons. The experiments described here indicate that a Marx + POS system may be capable of providing enough energy in a single pulse (more than 100 kJ) and produce a sufficient number of  $^7\text{Li}$  (or  $^{19}\text{F}$ )  $\gamma$ -rays for future detection applications.

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